How A Radio Tube Makes A Weak Signal Stronger

LESSON ND-13

SPRAYBERRY ACADEMY of RADIO

ESTABLISHED 1932

PUEBLO, COLORADO

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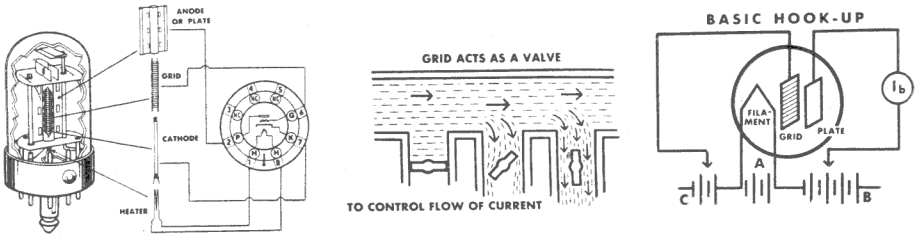
When a radio signal reaches the antenna or energy collecting system of a receiver it is *comparatively weak*. In fact, it is much too weak to operate the usual sound reproducer (speaker) so as to give a satisfactory level of audible sound waves. This is one of the prime reasons why a vacuum tube is necessary — to build up the strength of a received signal to a useful level.

To understand what must be done to a signal once it is received consider its basic form. First of all, it should be understood that it is a high frequency signal—much too high in frequency for the human ear to hear it. So, besides being extremely weak when it is received, it is in the wrong form for direct use. Thus, the first job to be done to a received signal is to build it up in strength. The section of a radio set which does this is called the R. F. (radio frequency) amplifier. This section includes tubes and various tuned circuits. The tubes increase the strength of the signal and the tuned circuits permit just the one signal to be selected out of all others. Thus, the R. F. amplifier provides strength and selectivity. The latter term will be given adequate treatment in other lessons. Adding strength to a signal or building it up to a higher level is called *amplification*.

After the signal has been selected and properly amplified its frequency must be changed. There are two commonly accepted methods of doing this—each employing a different type of circuit. The final result of either method is a change of the signal frequency from a relatively high value to a low A. F. (audio frequency) which will operate a speaker. The changing of the signal frequency from R. F. to A. F. is called *detection or demodulation*. The two types of circuits previously mentioned are really types of receivers. The first and older type employs a T.R.F. (tuned radio frequency) circuit. In this method, the signal is built up to the desired level by one or more R. F. amplifier stages and then fed to the detector (the tube that changes the frequency) .In the second and much more popular type of receiver, a *superheterodyne* type of circuit is employed. In this type of circuit, the signal goes through two frequency changes before it is fed to the A. F. amplifier. As in the T. R. F. circuit the signal is first selected and built up to the desired level. It is then fed to what is known as a first detector or mixer stage. Into this stage is also fed a signal or frequency from a local oscillator stage. The two frequencies (the received signal and the one from the local oscillator) are then *mixed* in the first detector stage. The result is a *new fre-*

TRIODES



The above shows a pictorial view of the triode tube in action. At the left is shown a triode tube of the lock-in type. Next in line shows how the tube elements connect to the tube socket. The center illustration shows how the grid acts as a valve. The schematic diagram to the right shows the usual connections as they would appear in a radio diagram. Courtesy of Sylvania.

quency which is fed to an I. F. (intermediate frequency) amplifier, and it in turn, feeds into a second detector or demodulator tube which accomplishes the same thing as the detector in the T.R.F. type of receiver— that is, reduces the signal in frequency to a low A. F. value.

Regardless of the type of circuit used after demodulation or final detection, the signal is again relatively weak and tubes must be used in an A. F. amplifier circuit to build the signal up to the level required to operate a speaker at comfortable room volume. So from this brief explanation it ought to be clear to you that there is a definite need for amplifier circuits which require and must have radio tubes in order to operate.

The foregoing should not be taken as a complete explanation of T.R.F. and superhetrodyne circuits, selectivity, oscillators, R. F. and A. F. amplifiers, etc. They have been mentioned at this point to give you a definite picture of *why radio tubes are needed and why you must study them.* At the proper point in your studies, these new subjects will be introduced and given detailed explanation. So don't think this is all the instructions you are going to get on these subjects.

To return to the vacuum tube, it of itself is not very useful unless proper circuits are associated with it. For a tube to provide amplification there must be a method of feeding a signal to it as well as taking the signal away from it after the tube has done its work. That part of a circuit which feeds a signal to a tube is called the *input* and that part which feeds the signal on to some other unit is called the *output. Thus every tube has an in-out and output circuit.* Further on in this lesson, we will return to the input and output circuits.

THE GRID AS THE THIRD ELEMENT IN A TUBE

In a previous lesson it was mentioned that Dr. Lee DeForest developed the idea of a third element in a tube which he called a grid. With this discovery, the way was opened up for modern radio and television as we know it today. You will remember in the description of the diode tube the fact was brought out that its operation was made possible by the cathode emitting electrons which in turn were attracted by the positively charg-

ed plate. This emission of electrons is roughly comparable to steam evaporating from a boiling teakettle. In other words, *clouds of electrons* are thrown off by the emitter or cathode.

Not all of the electrons emitted by a cathode actually reach the plate, especially in a diode tube. There is a saturation point for a given value of plate voltage. This means, as explained in a previous lesson, that the plate will only attract so many electrons for a given plate voltage. For it to attract more electrons, the plate voltage must be *increased.* This is called plate voltage saturation. Another type of saturation is called temperature saturation wherein if more electrons are to be emitted by the cathode its temperature must be increased. It is not practical to control the flow of electrons by varying the cathode temperature, and besides, this shortens the life of a tube especially if a certain limit is exceeded for a given tube. Tube manufacturers, therefore, design a tube for a rated heater voltage and recommend that the tube be operated at or near this value. Also it has been proven that it is not satisfactory to control the electron flow by varying the plate voltage. So some other means must be employed to control the flow of current. The third element or grid provides this control to a very precise degree.

THE SPACE CHARGE

It must be evident to you by this time that there is a very definite reason why there are saturation limits to the heater temperature and plate voltage. In other words, why doesn't the *space within the tube* act like any other conductor and so conduct the maximum amount of current? The reason for it is an effect within the tube in the space between the cathode and plate. It is called the *space charge effect.* In reality what happens is that a cloud of electrons collect between the cathode and plate. This cloud of electrons is nearer to the cathode than the plate. In fact, they surround it entirely and actually form a *barrier or obstacle* to the free flow of electrons as they leave the cathode.

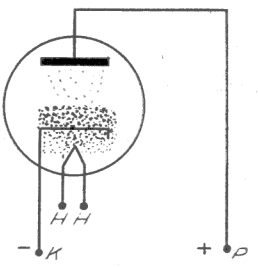


FIG. 1

This electron idea is illustrated in *Fig. 1* which shows an exaggerated symbol of a diode tube. It is the indirect heater type employing a separate cathode. It is assumed that a suitable heater voltage is applied to the H-H terminals and that a source of D. C. is connected to the terminals K and P. The electron cloud of the space charge is symbolized by a heavy concentration of dots around the cathode with a few of them shown going over to the plate—representing normal current flow.

When current is first turned on and plate current begins to flow, a cloud of emitted electrons begins to collect around the cathode because, due to the saturation limit of the plate, it cannot attract all of the electrons. In theory, the plate voltage might be increased to the point

where it would attract *all* of the electrons liberated by the cathode. In practice, this point is never achieved because the plate element would heat excessively and might melt. Should this happen, no useful purpose would be served because there would be no control over the flow of electrons (current). A control must be attained over the flow of current before the tube can be useful as an amplifier.

As soon as the space charge forms, a certain few of the electrons reach the plate. However, a condition is soon reached where the electrons forming the space charge begin to *repel* the emitted electrons, forcing them back into the cathode thereby reducing the flow of current. The space charge being negative and very dense, can easily repel the emitted electrons back to the cathode. Some few electrons of very high speed do get through the space charge and reach the plate. Too, as conditions permit the plate to draw electrons unto it, some of those making up the space charge move on to the plate, and others from the cathode, move into the area of the space charge to replace those which have gone on to the plate.

When the condition is reached where the space charge repels electrons back to the cathode, the space charge momentarily becomes more *negative than the cathode.* The plate at the same time is taking electrons from the space charge and balance is soon restored until the space charge again increases in force and starts to repel electrons back to the cathode. Thus a cycle of events occur wherein the space charge acts as a relay between cathode and plate. It is because of this action that the space charge is sometimes called the *true or virtual cathode.*

The chief problem then in vacuum tube design is to obtain some method of control over the space charge. Since control of filament temperature and plate voltage has not proven satisfactory, some other means must be employed. Not only must the space charged be controlled, it must also, in many cases, be reduced. In other cases, it must be speeded up in its action so as to increase the flow of current to the plate. The grid and *other elements* of modern vacuum tubes are made to act on the space charge, and in that way control tube action. Many modern tubes have up to six, seven and eight elements—all of them in one way or another have an effect on the space charge. You will learn how all of this is accomplished in the next few lessons.

GAS REDUCES SPACE CHARGE

One way of reducing the effect of the space charge is to include a small amount of gas within the tube envelope. Several types of gas may be employed for this purpose. In rectifier type tubes the mercury vapor (heavy type gas) tube is an outstanding example of the use of gas to reduce the effect of the space charge. You will remember you studied about this tube in a previous lesson. When dealing with rectifier tubes, the object is to obtain large values of current flow with low values of voltage drop across the tube. In amplifier circuits a more accurate

LAVA · MICA · TIN · SODIUM CARBONATE · MONEL · SILVER OXIDE

SODIUM ALUMINUM FLUORIDE · RESIN (SYNTHETIC) · ETHYL ALCOHOL

MATERIALS USED IN RCA RADIO TUBES

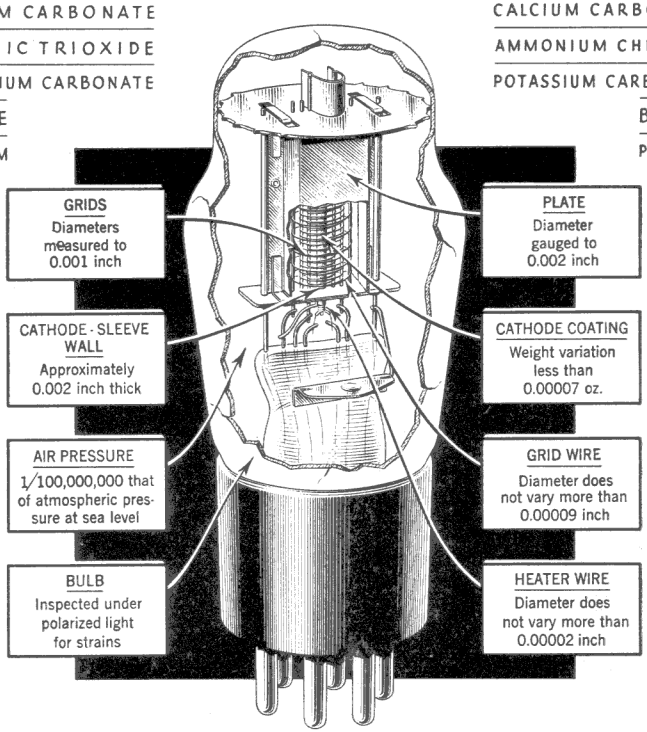
LEAD ACETATE · MALACHITE GREEN · GLYCERINE · ZINC CHLORIDE · IRON

MARBLE DUST · WOOD FIBER · STRONTIUM NITRATE · LEAD OXIDE · ZINC OXIDE

MISCH METAL · NIGROSINE · PORCELAIN · PETROLEUM JELLY · ZINC

BARIUM CARBONATE
ARSENIC TRIOXIDE
STRONTIUM CARBONATE
ISOLANTITE
MOLYBDENUM
ALUMINA
BORAX
BARIUM
COPPER
CARBON
CHROMIUM
CALCIUM
CAESIUM
COBALT
SODIUM NITRATE
MERCURY
CALCIUM OXIDE
BARIUM NITRATE

CALCIUM CARBONATE
AMMONIUM CHLORIDE
POTASSIUM CARBONATE
BAKELITE
PHOSPHORUS
SILICON
SHELLAC
TUNGSTEN
TITANIUM
SILICA
GLASS
MAGNESIA
PLATINUM
STRONTIUM
MAGNESIUM
ROSIN
NICKEL
COBALT OXIDE
THORIUM NITRATE



Gases Used in Manufacture

NEON — HYDROGEN — CARBON DIOXIDE — ILLUMINATING GAS
HELIUM — ARGON — NATURAL GAS — NITROGEN — OXYGEN

Elements Entering into the Manufacture

ARGON — ALUMINUM — BORON — BARIUM — CAESIUM — CALCIUM — COPPER — CARBON — CHROMIUM — CHLORINE
COBALT — HYDROGEN — HELIUM — IRIDIUM — IRON — LEAD — MAGNESIUM — MERCURY — MOLYBDENUM
NICKEL — NEON — NITROGEN — OXYGEN — POTASSIUM — PHOSPHORUS — PLATINUM — SODIUM — SILVER
SILICON — STRONTIUM — TUNGSTEN — THORIUM — TANTALUM — TITANIUM — TIN — ZINC — RARE EARTHS

From examination of the above presentation you will see that many items are used in the manufacture of radio tubes. Not all of the items listed are used in making the type of tube shown, but different type tubes do require all or part of these various items during the process of manufacturing. Courtesy of R. C. A.

means of control is wanted than is obtainable by controlling filament temperature, plate voltage or by using gas. The grid or third element gives this control effectively as you will soon learn.

To return to the mercury vapor tube, it reduces the effect of the space charge in the following manner. An electron liberated by the cathode travels at high speed to the plate unless the space charge becomes too dense. When current is first turned on the space charge does not exist. Therefore, the first few emitted electrons get over to the plate almost at once. In traveling to the plate, the first few electrons encounter on their way *atoms* of the mercury vapor. They are traveling at high speed and collide with the mercury atoms. This collision of electrons and atoms causes more free electrons to be liberated from the mercury atoms and, being at this point more under the influence of the positive plate than the negative space charge, the original electrons and those liberated from the mercury atoms immeditely move over to the plate. In the meantime, the original mercury atoms now become *mercury ions* (having lost electrons they become positively charged) and being positively charged and located nearer the plate than the cathode, the plate immediately repels them toward the space charge and cathode. The latter being negatively charged also exerts an attraction on the mercury ions. When the ions reach the space charge, they at once take on enough electrons to restore their electrical balance and they become mercury atoms again. The mercury ions having drawn unto themselves electrons in the space charge it means electrons can now leave the cathode and enter the space charge to replace those which have entered into the atomic structure.

This cycle of events is repeated over and over again. The net effect is a gain of electrons reaching the plate over the number which would reach it if there was no mercury vapor present. The foregoing description has applied to to just a few electrons and mercury atoms. Multipy this effect many millions of times and you will realize how easy it is for the mercury vapor to reduce the normal effect of the space charge. This is a fixed control of the space charge sealed within the tube. For amplification, we need a control external to the tube so that as the received signal is applied to the tube it may be made to *act on the space charge.* The grid as previously mentioned provides this control and is, in effect, a variable control—a condition necessary to handle a varying signal.

THE CONTROL GRID

A diode tube contains two electrodes or elements—*the cathode* and *plate or anode.* When a grid is added to the tube structure it is called a *triode,* meaning one having three useful elements. Such a tube may also have a fourth element in the form of a filament, but it is not counted as a useful element if the tube employs a separate cathode. If no separate cathode is employed, then the filament becomes the cathode and, in this case, is counted as an element. The third element or grid in most cases

is called a *control grid* because it controls the signal, and further, this term is used to avoid confusion with other grids which are included in other type tubes.

The location of the control grid is adjacent to the cathode in the region where the space charge exists. This element is not solid metal but is made in the form of an open mesh similar to common wire screen. It may also be in the form of a wire spiral or other similar forms. The object of this construction is to provide several openings in the grid structure so electrons can pass through the grid on their way to the plate.

Thus it is seen that the control grid is exactly in the path of the electrons and none can get over to the plate from the cathode or space charge without the grid exerting its influence on them. Therefore, by applying a voltage source to the grid it can be made to slow down and increase the flow of electrons, depending on the polarity of the charge on the control grid.

GRID CONTROLS ELECTRON STREAM

Your previous studies of electric lines of force will be useful at this time. You will remember when an electric charge exists (either polarity) between two conductors, electric lines of force are present, and reach out into space to a distance, depending on the value of voltage representing the charge. These electric lines of force may be made to guide *free electrons*. It should be clear from this explanation and your previous studies that a charge placed on the grid of a tube will, therefore, by means of its electric lines of force exercise great control over the free electrons making up the space charge. There are magnetic effects present, too, but the principle method of control over the free electrons is by electro-static action.

This control of electrons by electrostatic lines of force may be illustrated as in *Fig. 2*. This shows roughly the conditions which exist in a triode tube. The large dots in the center of the plate and cathode represent the spiral wires of the grid. The entire grid structure cannot be shown in this figure because it is not in the same plane as the cathode and plate. The cathode and plate are represented in this figure as two parallel plates of a condenser. Only the general idea of electrostatic control of the electrons is supposed to be illustrated by *Fig. 2*. In practice, the cathode and plate are not as symmetrical as represented by this figure. However, they do to some extent act as the plates of a condenser. Thus there is established between them electrostatic lines of force. In addition, when a charge is placed on the grid other lines of force come into being and exist between the

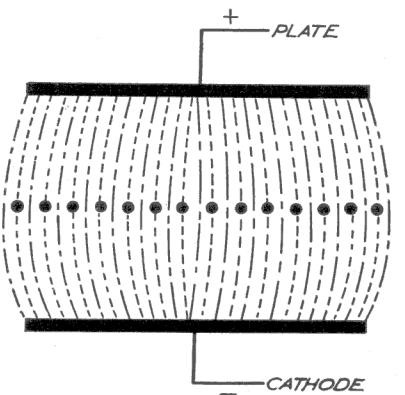


FIG. 2

grid and plate as well as between the grid and cathode—but the greatest effect of these is between grid and plate. Thus the lines of force in *Fig. 2,* represented by the *dash lines,* can only be symbolic of the total lines of force, and so do not represent just those of the grid or those between plate and cathode alone. The *dot-dash* lines in *Fig. 2* represent the path taken by the electrons as they travel from the cathode to the plate. Study *Fig. 2* and note the grid is directly in the path of the electrons and none can pass it without being under the influence of the charge existing on the grid. This charge by means of its electrostatic lines of force reaches out to a considerable distance away from the grid wires. Therefore, the acting influence is not just at the grid wire itself but also exists in the space adjacent to each grid wire. From this you can see that lines of force radiated from the grid wires can exert influence on moving electrons even though they do not come into contact with the actual grid. These lines of force actually guide the electrons in their flight from the cathode to the grid. *An important principle to recognize and remember from this action is that the grid can exercise its control over the electrons even though there is no grid current flow either internal or external to the tube envelope. It is just the electrostatic action alone (voltage charge radiating lines of force) that acts on the electrons—current does not have to flow in the grid circuit for this action to occur. This is comparable to condenser action wherein it retains a charge and lines of force exist between its plates without there being a current flow.*

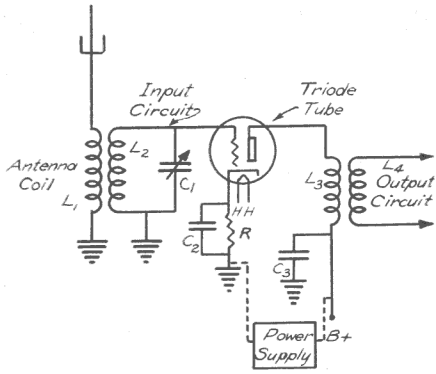


FIG. 3

INPUT AND OUTPUT CIRCUITS

Before studying the action of the control grid within a triode tube, you should first understand about its *input and output* circuits. *Fig. 3* shows one type of R. F. circuit for a triode tube. Note the several *ground* symbols in this circuit. This indicates all the grounded parts of the circuit connect to the metal chassis of the receiver or to one *common point.* Usually a metal chassis is used and you should remember that it is a common conductor for several circuits. Thus the connections of the lower ends of coils L1 and L2 to ground *is the same thing as connecting them together.* The same principles hold true for the other grounded parts.

The input circuit for a tube is that which exists across its control grid and cathode. Thus L2-C1 of *Fig. 3* represents the signal input to the tube—the signal voltage being induced from L1. You will recognize that L2-C1 forms a series resonant circuit. Since the cathode of the tube is grounded through R

and C2 and since one end of L2-C1 is grounded, these two points are effectively connected together to form a common circuit. The purpose of R in series with the cathode is to form a voltage drop across it to be applied as a negative voltage to the control grid—more details of this function will be given later. Condenser C2 is called a by-pass around R. Its purpose is to keep high frequency currents from entering R since its reactance in ohms offers less resistance to high frequencies than does the resistance of R. These are details to be brought out later.

For the *output circuit* of the triode tube in *Fig. 3,* L3 and L4 serves this function. Variations of plate current of the tube set up varying lines of magnetic force in L3 and this induces a corresponding voltage in L4. The circuit of L4 may, in turn, feed the grid of another tube or any other suitable device. The purpose of C3 in *Fig. 3* is to keep high frequency currents from the plate out of the power supply and to help smooth the rectified D. C. fed to the plate. The positive of the power supply connects to the plate and the negative of the power supply connects to ground. Since the cathode and negative of the power supply are grounded, an effective circuit is formed between plate and cathode. This, in turn, fulfills the conditions for the output circuit, for before the output circuit is completed, a circuit must exist between plate and cathode. Note that this means the *cathode is common to both the input and output circuits.* Be sure to keep this fundamental fact in mind.

Note in *Fig. 3* that there are three voltage sources: (1) The heater or filament voltage which may be either A. C. or D. C.; (2) The plate voltage which must be D. C., and (3) Control grid or grid voltage which also must be D. C. It is common practice in the radio industry to refer to the filament supply as the "A" supply, the plate supply as the "B" supply and the grid supply as the "C" supply. More often the reference is simply A voltage ,B voltage and C voltage. You should memorize these definitions.

From the foregoing explanation, you will now understand that a radio tube must employ an input and output circuit before the grid can be made to exercise its control over the space charge. With this understanding, you are in a position to appreciate the fundamental actions of the triode tube, and you will soon understand the reason for the following detailed study.

Dr. DeForest found upon employing a grid that the output voltage of a triode tube *could be made greater than the input voltage.* In other words, he had discovered amplification, which meant making it possible to strengthen the very weak output of the diode. It is but a small step from a consideration of the diode, *Fig. 4,* to a triode, so you should now refer to *Figs. 5* and *6.*

TRIODE TUBE SYMBOLS

Fig. 5 shows the electrical symbol of a filament or direct heater type of triode tube such as you will find in the usual schematic diagram. Try to remember this fundamental symbol. *Fig. 6* shows the physical arrangement of the ele-

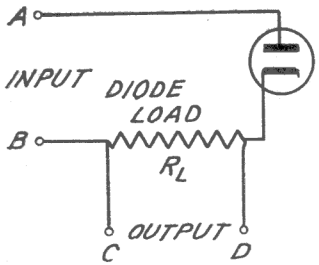


FIG. 4

ments of an indirect heater or cathode type of triode tube. Study this figure and try to keep in mind this physical arrangement of the triode tube elements as you continue your study of this lesson.

There are several types of triode tubes in common use. Two of these are the 30 and 56 types. There are later type tubes but they all operate on the same general principles, so these two types will serve to illustrate the several types of triodes in common use.

The 30 type represents the direct heater or filament type of tube. The 56 represents the indirect heater or cathode type of tube. These two types of construction are shown in *Fig. 7*.

First consider the 56 triode. *Figure 8A* shows a cross section of this type of tube. The cathode, the grid wires and the plate are shown. If the cathode is heated by the hot filament and the plate has a positive charge (placed there by a bat-

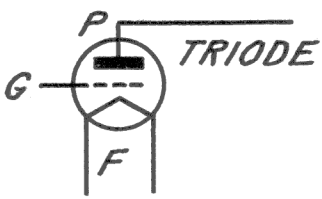


FIG. 5

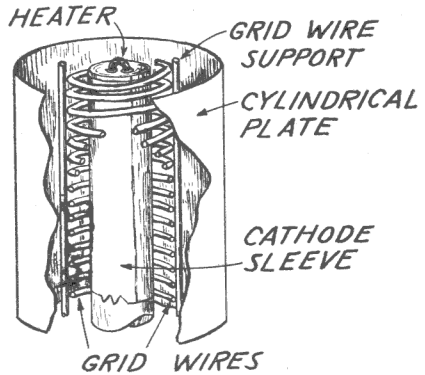


FIG. 6

tery or an A. C. power supply), the positive plate will attract (through the space between cathode and plate) negative electrons being thrown off by the cathode. The grid, while located between the plate and cathode, will not *obstruct* (except to a very small degree) the flow of electrons *as long as its votage is zero.* A few of the electrons will collide with the grid but not very many—not enough to have a noticeable effect on the pate current.

A. C. ALTERNATES CHARGE ON GRID

Also, if the grid is not connected to a voltage source it will not control the electrons. However, being in the region of the space charge the grid can under certain conditions collect a negative charge and so block the normal flow of current

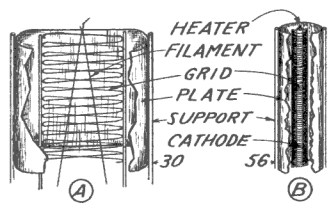


FIG. 7

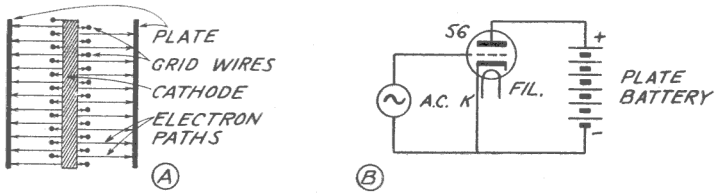


FIG. 8

if it is left free and not connected externally. If the grid is connected properly it can *control* practically all of the electrons being attracted by the positive pate. To illustrate this control action in more detail, consider an A. C. signal generator connected in series with the input of the grid and cathode of a triode tube as shown in *Fig. 8B*. This generator will make the grid alternately positive and negative with respect to the cathode. In other words, when the grid is positive, the cathode will be negative due to the polarity of the A. C. wave form and vice versa.

As the *grid becomes negative* due to the A. C. generator some of the electrons from the cathode which are trying to get to the positive plate will be *repelled back to the cathode because like charges repel.* Under this condition both the electrons and the grid are now negative or charged alike. Remember the grid is located in the space charge between the plate and cathode, and can therefore, easily repel the electrons before they reach the plate if the charge on the grid is of sufficient magnitude.

When the A. C. signal voltage reverses, the grid becomes positive and the cathode negative. Since the *grid is now positive, it will attract* the negative electrons and *increase their speed* on the way to the plate. The reason the electrons continue on to the plate from the grid is because the plate is at a much higher positive charge than the grid. All of this is fundamental, and *Fig. 8B* merely illustrates a principle. In practice, *the grid of an amplifier tube is never allowed to become positive,* as you will learn later on in this lesson.

You will now realize that when a grid is positive, the plate current from the plate circuit battery is *increased* and when the grid is negative, the plate current is *decreased.* In one case *more electrons reach the plate* and in the other case, *less electrons reach the plate.* In other words, the grid is controlling the flow of electrons.

At this point, it is most important for you to understand just what this means. *The grid is placed in the tube for the sole purpose of controlling the plate current* (meaning the flow of electrons). The space between the cathode and plate acts as a *resistance and places a load* equal to what we may call a value Ro on the plate battery. It is this Ro (includes the effect of the space charge) *which limits the flow of plate current* (D. C) from the plate battery.

If A. C. or a radio signal is applied to the grid, the effect it has on the D. C. plate current will be to make it increase and decrease as the grid voltage changes. The resulting *ripple or variation in the*

plate current is small as compared to the total D. C. which is flowing. It is most important for you to realize the full significance of this statement. It means in effect that there are *two plate current components*—one D. C. and the other an effective A. C.

Don't misunderstand this statement. It does not mean that the plate current completely reverses, because current can only flow through a tube in one direction. What it means is that, the D. C. plate current *varies or changes from a minimum to a maximum* within certain narrow limits. Instead of the current being a pure A. C., it is a pulsating D. C. which, for all practical purposes, may be considered as A. C. of sine wave form. (for definition of a sine wave, see your S. A. R. dictionary). The variation in current is the only useful part, and it must be strong enough to set up useful changing lines of force. This will make it possible to transfer energy from one circuit to another. If there is an effective A. C., then it follows that there must be something *which limits the flow of A. C.* This limiting factor is called the Rp of the tube—meaning *the A. C. plate resistance.* If a distinction is not carefully made between the D. C. resistance of a tube which we call Ro, and its effective A. C. resistance Rp, confusion can easily result. Therefore, we will consider the D. C. resistance first even though it has less importance than the A. C. resistance in the consideration of fundamental tube principles. A consideration of the D. C. resistance can be effectively employed however, to show how a triode tube can be made to amplify or give strength to a weak signal. It, of course, does not tell the whole story, as there are too many other factors involved. These will be brought out in greater detail later on.

TUBE ACTS AS VARIABLE RESISTANCE

You will remember in a previous lesson it was stated that the space between the cathode and plate of a diode tube could be regarded as a resistance from a D. C. viewpoint. In fact, this space is actually a variable resistance as will now be brought out.

Still considering the diode type of tube, refer to *Fig. 4.* If an A. C. or a varying radio signal is impressed across the input terminals A and B, a rectified current will flow through the load resistor R_L as you have learned from previous studies. Assuming a peak A. C. input voltage of *instantaneous value,* the result will be a flow of current of definite value. With these conditions where a constant value of voltage and current can be assumed, the diode circuit of *Fig. 4* can be simplified to an equivalent D. C. circuit consisting of an internal D. C. resistance Ro and an external load resistance R_L as in *Fig. 9.* The signal is symbolized in this figure as a battery E, having a steady or fixed value of 28.2 volts. Any other reasonable value for E could be assumed and the results would be the same. So the particular value of E has no special significance except to illustrate the principle involved. Note Ro in *Fig. 9* is symbolized as a variable resistance and we will now show why this is necessary.

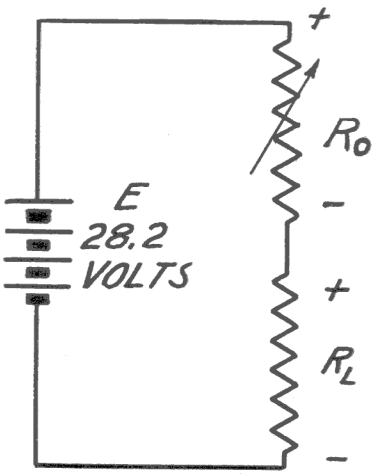


FIG. 9

In radio we are continually having to do with varying conditions, because the radio signal itself is always varying and practically every part in a radio circuit has its counterpart in this varying action. On this same principle, the load R_L in *Fig. 9* may be varied to show the effect of this variation on Ro, the internal D. C. resistance of the diode tube in *Fig. 4*.

Before going into this, it is necessary to explain that if we assume the A. C. signal fed to the circuit as having a value of 20 volts R. M. S., the battery E will have to have a value equal to 20x1.41 or 28.2 volts if the peak value of the A. C. signal is not to be overlooked. From this explanation, you will now see how the value of the battery E of 28.2 volts in *Fig. 9* was obtained.

A practical value for R_L in Fig. *9* is 250,000 ohms and a practical value for the plate current is 95 microamperes. For these values the voltage drop across R_L will be 250,000x.000095=23.75 volts.

This means that the voltage drop across Ro of the tube is equal to 28.2 minus 23.75=4.45 volts. The value of Ro for this condition is found from ohms law in that

$$\text{Ro} = \frac{4.45}{.000095} = 46{,}842 \text{ ohms.}$$

The next step to illustrate the action of the diode tube is to show what happens when the load resistance R_L is changed from 250,000 to 500,000 ohms with 28.2 volts maintained at the input. A practical value for the plate current under these conditions is 50 microamperes. The voltage drop across R_L will in this case be equal to

$$\frac{3.2}{.00005} = 64{,}000 \text{ ohms.}$$

In the foregoing two examples note that in one case Ro equals 46,842 ohms and in the other case 64,000 ohms. The only physical change made in the circuit is the value of the load resistance R_L. This does not represent true conditions because, in practice, the signal voltage is not constant, but changes in value from zero to maximum peak values and the load resistor R_L remains at a fixed value. This means that the Ro or the D. C. resistance of the tube changes as the signal changes. *Thus in effect it is a variable resistance.* You want to be sure and remember this explanation, because it is often employed in practical radio circuits.

The purpose of the foregoing explanation is to prove that the output voltage of a diode circuit is always less than the input voltage. In other words, a diode tube *does not* amplify or strengthen a signal.

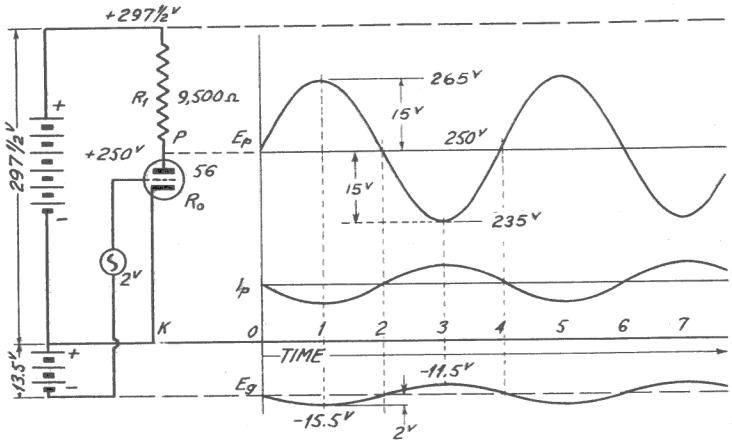


FIG. 10

Keep this fact in mind as you study the following explanation on the triode tube, for when a grid is added to the diode it becomes a triode *and will give more voltage at its output than is fed to its input* thereby providing amplification.

HOW A TRIODE TUBE AMPLIFIES

The conditions under which a triode tube operates are rather definite and it is possible to show reasonably precise actions by means of a diagram and a graph. Such a presentation is shown in *Fig. 10.* It should be studied long and carefully because it shows the general theory of what takes place when the tube amplifies a signal. Note the complete figure is divided into two sections as denoted by the straight vertical line just to the left of center of the picture. The left section shows a 56 type triode tube wired for normal operation. The right section is a graph of the various wave forms produced by the tube.

Between the grid and cathode circuit is connected a peak 2 volt A. C. signal generator. Note this is also in series with a 13.5 volt C battery. Trace out the grid circuit from the grid to the cathode and satisfy yourself that the 2 volt signal generator and 13.5 volt battery are actually in series between grid and cathode. Next note the plate of the tube uses a 9500 ohm load resistor R_L. Then note that a 297.5 volt B battery is in series with the plate, R_L and the cathode of the tube. Note, too, the point where the C and B batteries connect. Both of these connect to the cathode of the tube at a common point. The negative of the B battery and the positive of the C battery are connected to the cathode. This makes the plate of the tube *positive* with respect to the cathode while the reverse polarity of the C battery makes the grid of the tube *negative* with respect to the cathode. The filament of the tube is not shown but it may be assumed to be present and properly heating the cathode to allow it to emit electrons.

Now for the right section of

Fig. 10. At the top of it you will notice a sine wave form labeled Ep of greater amplitude than the two smaller wave forms below it. The abbreviation of Ep refers to plate voltage—that is, the effective A. C. wave form in the plate circuit of the tube. The center wave form labeled Ip in *Fig. 10* represents the plate current of the tube. The lower wave form labeled Eg of much smaller amplitude than the other two wave forms represents the effective input voltage to the grid.

This right hand section of *Fig. 10* is a graph which shows all the conditions for a triode tube as it amplifies a signal. From this you can see exactly what takes place on every point of the cycle for the three properties involved. Namely, grid voltage, plate current and plate voltage. Note the time line just under the Ip curve. This divides the cycles in units of ¼. Thus time 1 corresponds to ¼ cycle, time 2, ½ cycle, time 3, ¾ cycle, time 4, 1 cycle, etc. More interesting points will be brought out for this graph later on.

For the conditions stated for the tube in Fig. 10 there will be a 47.5 voltage drop across R_L which is in series with the plate of the tube. Since 47.5 volts is lost across R_L this leaves 250 volts between plate and cathode of the tube. The plate current in the tube circuit is .005 ampere. Manufacturers' literature states that with 250 volts applied to the plate of a 56 type tube its grid voltage should be 13.5 volts *negative*. So in Fig. 10 a 13.5 volt C battery is shown connected betwen cathode and grid to fulfill operating conditions for the tube.

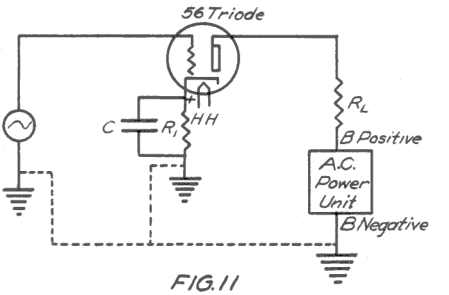


FIG. 11

These are all values with no input signal applied to the grid of the tube. When a varying signal is applied to the grid all of these values except R_L change within narrow limits as will be brought out at the proper time.

It is interesting to note that this 13.5 volt C bias, as it is often called may be obtained by connecting a suitable resistor between cathode and ground—the return lead of the grid also being grounded. The circuit for this arrangement is shown in Fig. 11 which is an exact duplicate of the triode circuit of Fig. 10 with the exception that it is entirely A. C. operated. As with the usual A. C. power unit the negative terminal of this one is grounded. Note, too, resistor R as well as the grid return circuit is grounded to the chassis of the receiver, making all three of these points connect to a common circuit.

The value of R1 in Fig. 11 as usual is found from ohms law in that $R = \frac{E}{I}$. The wanted voltage on the grid of the tube is 13.5 volts. The plate current of the tube is .005 ampere and since it must flow through R1 the value of the latter may be found from $\frac{13.5}{.005} =$

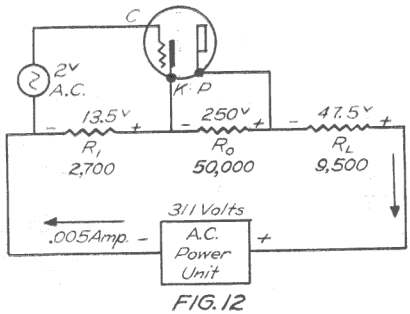


FIG. 12

2700 ohms. Thus with .005 ampere flowing through a resistance of 2700 ohms a voltage drop of 13.5 volts is *made to occur across the resistor R1.*

The voltage applied to the grid of any tube is that amount of voltage which exists between the cathode and grid of the tube. Current flowing through R1 enters at its grounded end and leaves it at the cathode of the tube. Thus the grounded end of R1 is the most negative part of the tube circuit. This, of course, makes the cathode end of R1 more positive than its grounded end — the exact difference in voltage being 13.5 volts. At the same time, the plate of the tube is more positive than the cathode because it is at a much higher potential of 250 volts. Since the grid return is grounded or connected to the grounded end of R1 and since grid voltage is that which exists between grid and cathode, it follows that the grid is made 13.5 volts negative because that is the amount of voltage existing between cathode and grid.

GRID ALWAYS NEGATIVE

This idea of a negative voltage on the grid of a tube is better understood by referring to a circuit like Fig. 12. Here all current carrying units in the tube circuit are shown as resistors. R1 is the same as R1 in Fig. 11, which provides the grid bias voltage. R_O is the internal tube resistance to the flow of D. C. found by dividing 250 volts by .005 ampere. R_L is, of course, the load resistor. Note R1 R_O and R_L make up a series voltage divider across the A. C. power unit whose output voltage is 311 volts D. C. Note, too, there is a voltage drop of 13.5 volts across R1, 250 volts across R and 47.5 volts across R_L. These total exactly 311 volts — the output of the power unit. Thus we have accounted for the full voltage of the power unit. For these conditions, the power unit of Fig. 10 must equal 311 volts because there is only one source of voltage for Fig. 12 where as in Fig. 10 there are two voltage sources; namely, a C battery of 13.5 volts and a B battery of 297.5 volts. Note, however, the two batteries total 311 volts so the two sources of voltage are exactly the same value for both circuits.

Study Fig. 12 and note how the negative voltage is applied to the grid. The grid does not draw current or power so the full voltage across R1 is applied to the grid. The grid of the tube is connected to the negative end of R1 while the cathode is connected to the positive end. Electrostatic lines of force exist between the grid and cathode inside the tube just as for any condenser. However, the surfaces of the grid and cathode are so small that very little condenser action can take place. For the usual 56 type tube, the capacity between grid and cathode is 3.2 mmfd. or .0000032 mfd. Hence little or no energy transfer takes place be-

tween these two elements of the tube. Yet enough electrostatic lines of force do exist between them to permit the grid to be charged to 13.5 volts negative and the cathode to 13.5 volts positive. You will remember this checks with your study of condensers wherein two condenser plates may be charged to a value equal to the voltage source. From the foregoing explanation, you should now fully understand how a grid may be maintained at a negative potential either by a battery or from the voltage drop across a cathode bias resistor.

Now that the basic conditions for operating triode tubes have been explained you are ready to study the various wave forms associated with it.

WAVE FORMS ASSOCIATED WITH A TRIODE TUBE

You have seen how the grid is maintained at a steady voltage of 13.5 volts negative. This does not accomplish anything other than maintaining operating condition for the tube. What happens when a radio signal is applied to the grid? To show what happens, we have assumed the use of an A. C. signal generator in series with the grid of the tube—see Figs. 10, 11 and 12.

Let this represent a relatively weak signal delivered to the grid of the tube by a suitable input circuit. This signal has a *peak* value of 2 volts. Since it is in series with the grid circuit, it is going to add and subtract to the C voltage of 13.5 volts subject, of course, to polarity.

Now what happens when voltages are connected in series? Quite naturally they add or subtract according to polarity. Thus when the A. C. generator is at a negative peak of 2 volts, the total negative voltage in the grid circuit is going to be $-13.5 + (-2) = -15.5$ volts. When the generator is at a positive peak, the total negative voltage in the grid circuit will be $-13.5 + (+2) = -11.5$ volts. In this latter case, you will note that the two voltages are of opposite polarity; therefore, the total voltage is equal to the difference between the two.

Thus by using a 13.5 volt battery and a 2 volt A. C. generator the grid voltage is made to vary from a minimum of 11.5 volts negative to a maximum of 15.5 volts negative. Note particularly from this that the grid *never becomes positive*. This is true even though the A. C. generator does give a positive peak. The total voltage still remains negative—all the positive peak does is to *reduce the voltage to a less negative value.*

You may wonder why it is desirable to maintain the grid negative at all times. There is a perfectly good reason for this. *If the grid were permitted to become positive it would attract some of the negative electrons and so prevent them from reaching the plate.* Thus there would be a flow of current in the grid circuit and less current flow in the plate circuit. This is undesirable because it would feed the signal energy back into the grid circuit whereas it is directed toward the plate circuit. Thus no useful purpose would be served.

For stable or useful operation of the tube, the grid must not draw power from the electron stream within the tube and there should be no current flow in the grid cir-

cuit—a voltage change is all that is wanted in this circuit.

This varying grid voltage effect is shown by the lower wave form in the graph portion of Fig. 10. It is marked Eg. Note it starts out from 13.5 volts in a negative direction and at time 1 (¼ cycle), is at a maximum *negative* peak of 15.5 volts. At time 2 (½ cycle), it has reduced to its regular grid voltage value of 13.5 volts. At time 3 (¾ cycle), it has advanced in the positive direction to its minimum *negative* value of 11.5 volts and at time 4, it has again reduced to 13.5 volts. For all succeeding cycles the same action takes place—the grid swinging to a maximum of 2 volts in both directions around a central reference of 13.5 volts.

It is the task of the grid to provide driving force for the tube. This force itself is not large in comparison to the potential force the grid can generate in the plate circuit. Yet the grid is so strategically located in the electron stream and space charge that *it has absolute control of what happens in the plate circuit.*

So keep this control action of the grid in mind while studying the plate action. You will want to know what happens to the plate voltage when the grid voltage varies continuously from −13.5 volts down to −15.5 volts and back to a minimum of −11.5 volts as shown by the grid voltage wave form in Fig. 13. This figure shows a magnified copy of the grid voltage wave form in Fig. 10. These values are the result of the A. C. voltage of 2 volts peak continually adding to and subtracting from the 13.5 volts D. C. already provided by the battery.

Starting from 0 at the grid voltage Eg wave form in Fig. 10, the grid voltage *swings* more negative to the first time unit or to point 1.

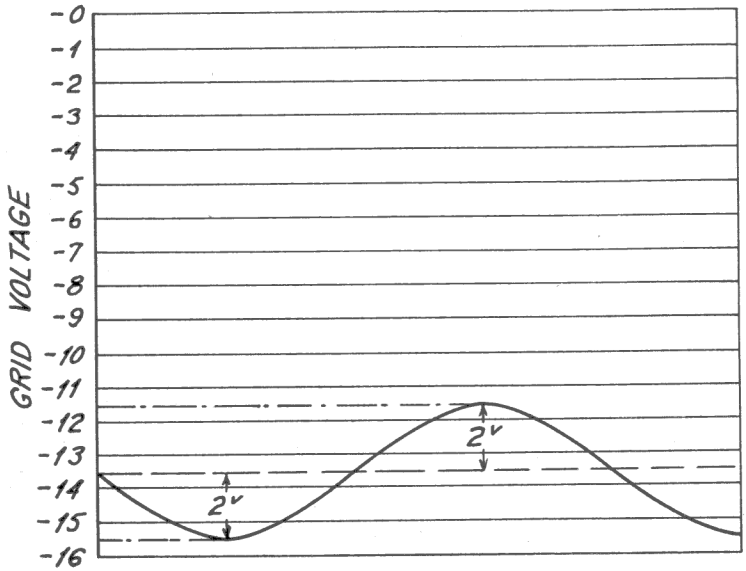


FIG. 13

During this time the electron stream from the cathode is being *reduced* as the negative grid voltage increases, the repelling action tending to force the electrons back toward the cathode. As a result, few of these actually reach the plate. This corresponds to *increasing the resistance* R_O of the space between the cathode and plate, *making the voltage drop across* R_L rise as indicated by the curve marked Ep in Fig. 10. Because the electron stream is reduced in intensity by increase of R_O, the current which is a measure of the number of electrons flowing is reduced. Note this corresponding reduction of plate current at curve Ip of Fig. 10 when Ep increases.

After passing the point of time 1 the grid voltage swings more positive, reducing from −15.5 volts to −13.5 volts at the time unit No. 2. The electron stream (current) again increases (with Ep decreasing) because the repulsion to electrons passing through the grid has been *reduced*. There is less repulsion when the grid is less negative. The Ep reduction is attended by an Ip increase as indicated by their respective curves in Fig. 10.

It is in this way that a voltage wave or variation is produced at the plate which is a *magnified copy* of the grid voltage wave form. Note in Fig. 10 the two are 180° out of phase—that is, as one (grid voltage) decreases, the other (plate voltage) increases. Note, too, that the *grid voltage and plate current* are in phase—that is, they uniformly increase and decrease together.

The relative increase of the plate voltage over the grid voltage is clearly shown by the amplitude of the Eg and Ep wave forms in Fig. 10. Ep, as you will note, is much larger than Eg. This means that within the tube the space existing between cathode and plate has strangely affected the signal voltage. It is within this space that amplification really occurs. It is brought about by a *growth of voltage* representing the increased velocities attained by the electrons over what their ordinary velocities would be if they were moving along a normal wire conductor. Of course, this is just part of the story, for the D. C. internal resistance R_O of the tube also plays its part wherein its resistance changes permitting a varying voltage change in the plate circuit. At the same time the electron action within the tube brings about the varying internal resistance of the tube so, in effect, the electron action within the tube and its varying internal resistance are really the same fundamental effect. The important point with respect to the D. C. resistance of the tube is that it allows us to have a *simple measure* of the electronic action within the tube.

The D. C. electrical equivalent of Fig. 10 is shown in Fig. 14. In this fiure, R_L represents the *external load resistor* in Fig. 10 while R_O represents the *internal D. C. resistance* of the tube. The point P in Fig. 14 represents the plate of the tube in Fig. 10. A is for the grid and K is for the cathode. As contact A is moved along the resistance element from K to P, the total resistance between K and P varies accordingly. This corresponds to varying R_O of the tube.

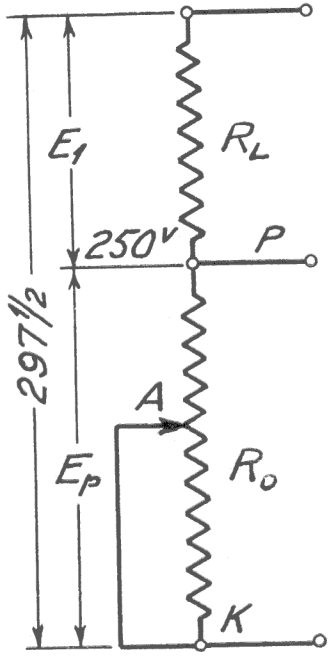


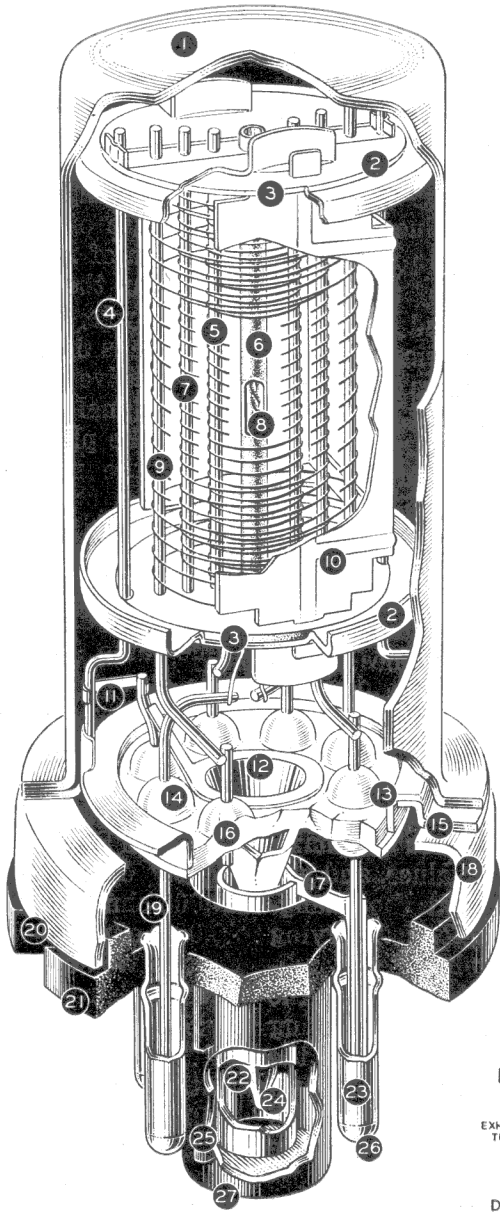
FIG. 14

The signal applied to the grid of the tube swings it from a minimum of 11.5 to 15.5 volts. The effect of this is to vary the electron stream within the tube thereby changing the internal D. C. resistance R_O of the tube. This corresponds exactly to varying R_O or contact A in Fig. 14 from minimum to maximum. From your study of the lesson on resistance you know that in a series circuit contining two or more resistors the voltage drop across each resistor is proportional to the total resistance value in ohms. *Thus, as the internal resistance of the tube changes, the voltage drop across the load R_L in the plate circuit changes in proportion,* even though it, itself remains at a fixed value.

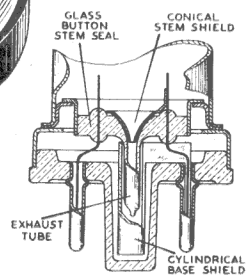
GRID CHANGES INTERNAL RESISTANCE

If R_O in Fig. 10 is made to have a value of 50,000 ohms due to the action of the grid, (no input signal or point of zero voltage in the signal cycle), there will be a voltage drop of 250 volts across it (note the applied voltage is 297.5 volts). For this condition, across R_L there will be a voltage drop of 47.5 volts (297-250). If R_O is now made to have a value of 40,000 ohms due to a change in grid voltage, the voltage drop across R_O will now be 240.5 volts and across R_L it will be 297.5 - 240.5 = 57 volts. If the changing grid voltage next makes R_O equal to 60,000 ohms, the voltage drop across the tube will be 256.84 volts and across R_L it will be 297 − 256.84 = 40.66 volts.

The foregoing three examples show how the grid of the tube by swinging through a cycle of voltage from 11.5 to 15.5 about a central value of 13.5, can make the R_O or internal D. C. resistance of the tube have three values of 40,000, 50,000 and 60,000 ohms, with 50,000 ohms corresponding to the central or reference value of 13.5 volts negative on the grid. Of course, these are examples only, and represent instantaneous values wherein certain grid voltages have been selected within the range of voltage applied to the grid of the tube. It should be clearly understood that the grid voltage is continuously changing and the three R_O values just cited are simply representative values. Actually, if the plate current of the tube varies from a minimum of .00428 to a maximum of .006 ampere as will be the case for 240.5 to 256.84 volts on the



1 METAL ENVELOPE
2 SPACER SHIELD
3 INSULATING SPACER
4 MOUNT SUPPORT
5 CONTROL GRID
6 COATED CATHODE
7 SCREEN
8 HEATER
9 SUPPRESSOR
10 PLATE
11 BATALUM GETTER
12 CONICAL STEM SHIELD
13 HEADER INSERT
14 GLASS SEAL
15 HEADER
16 GLASS-BUTTON STEM SEAL
17 CYLINDRICAL BASE SHIELD
18 HEADER SKIRT
19 LEAD WIRE
20 CRIMPED LOCK
21 OCTAL BASE
22 EXHAUST TUBE
23 BASE PIN
24 EXHAUST TIP
25 ALIGNING KEY
26 SOLDER
27 ALIGNING PLUG



DETAIL OF BASE SHIELDING

STRUCTURE OF SINGLE-ENDED METAL TUBE

This page shows a cutaway view of the metal envelope type tube. A study of these mechanical details will help you to form a better idea of the structure of the metal type tube. Courtesy of R. C. A.

plate, the internal resistance R_O of the tube is going to swing from a minimum of 40,000 to a maximum of 60,000 ohms. Thus R_O is not going to be a fixed value (although we can select instantaneous values for study purposes in order to make an analysis), but rather a continuous variable value.

Now, refer to Fig. 14 (which is the D. C. equivalent of the triode circuit in Fig. 10) and note that R_L and R_O are in series. R_L, the load resistance, remains at a fixed value. But, resistor R_O, on the other hand, varies. As previously mentioned in a circuit of this type where the resistors are in series across a voltage source, a change in resistance value of one unit will cause a proportional change of voltage across the other unit. Thus, when R_L in Fig. 14 becomes 40,000 ohms, the plate current is .006 ampere, resulting in a voltage drop of 57 volts across R_L. When R_O swings to 60,000 ohms, the plate current is .0042 and the voltage drop across R_L is 40.66 volts. These are maximum and minimum values, and you should remember that the changing voltage across R_L is varying from 40.66 to 57 volts. This condition has been brought about by the grid of the triode tube changing the internal D. C. resistance of the tube. To accomplish this, the grid has only changed from 13.5 to 15.5 or from 13.5 to 11.5 — a difference of 2 volts. The voltage drop across R_L, on the other hand, has changed from 40.66 to 57 — a range of 16.34 volts. For a normal no signal condition, or the point where the signal voltage passes through the point of zero voltage, the net negative voltage is 13.5 volts with a corresponding Ep of 250 volts. For a 15.5 negative voltage value on the grid, the corresponding Ep is 256.84 volts — an increase of 6.84 volts on the plate over the condition of no signal on the grid. For 11.5 volts negative on the grid, the corresponding Ep is 240.5 volts — a decrease of 9.5 volts from the condition of no signal on the grid. Thus, for the most negative peak of the cycle, the signal voltage at the plate is 6.84 volts while for the less negative or more positive peak of the signal cycle, the signal voltage at the plate is 9.5 volts. This means the negative and positive peaks of the cycle are *unequal*, whereas for ideal conditions, both peaks of the cycle should be the same — that is, 250 volts plus the same value and 250 volts minus the same value.

Note the reference values in Fig. 10 have been 250 volts at the plate, 50,000 ohms for R_O, representing conditions for no signal. From ohms law, you would think that with R_O made 60,000 ohms and 40,000 ohms — a difference of 10,000 ohms in each direction from 50,000 ohms — that the voltage change would be proportional, yet you see here that such is not the case because for 60,000 ohms, the voltage change at the plate is 6.84 volts, whereas for 40,000 ohms, it is 9.5 volts. *Thus, it is proven that ohms law does not hold true for a vacuum tube,* for if it did, the *voltage change* from 250 volts on the plate would be the same at 60,000 ohms for R_O as it is at 40,000 ohms. Other factors, such as non-uniformity of electron emission and variable grid action, enter into the operation of a triode

Ro	R_L	Ep	E_L	Eg	Ip
40,000	9500	240.5	57	11.5	.006
50,000	9500	250	47.5	13.5	.005
60,000	9500	256.84	40.66	15.5	.0042

tube, thereby affecting the R_O value and thus, it can be said to have a non-uniform characteristic.

All of the values pertinent for the triode tube of Fig. 10 are given in the above table. Study these carefully until you have a good understanding of the principles involved.

EQUAL PEAKS IN PLATE WAVE FORM

From the foregoing, it should be clear that in order to have equal peaks appear in the plate circuit for each half cycle of the signal, the Ro has got to change more in magnitude in one direction from 50,000 than in the other. Suppose we assume that equal peaks of signal voltage of 15 volts each are wanted in the plate circuit of a triode circuit similar to Fig. 10. For this condition, the positive peak of the cycle should equal 250 + 15 = 265 volts, and the negative peak should equal 250 − 15 = 235 volts. Thus, for these maximum and minimum values, the voltage drop across Ro, in one case, will be 265 and in the other, 235 volts. The value of the supply voltage is 297.5 volts. Thus, the voltage drop across R_L for an applied plate voltage of 265 volts is 297.5 − 265 = 32.5 volts, and for a plate voltage of 235 volts the drop across R_L is 297.5 − 235 = 62.5 volts. For the maximum value of plate voltage, the current is equal to $\frac{E_L}{9500} = \frac{32.5}{9500} = .0034$ ampere. Then, to find the value of Ro for these conditions, it is equal to $Ro = \frac{265}{.0034} = 77{,}941$ ohms. The minimum plate voltage value is 235 volts with 62.5 volts appearing across R_L, the current is equal to $\frac{62.5}{9500} = .0066$ ampere. The same current that flows through R_L must also flow through Ro. Therefore, the value of Ro is

$$\frac{235}{.0066} = 35{,}606 \text{ ohms.}$$

We now have the Ro values for maximum and minimum peaks of 15 volts plus and minus the normal plate voltage. The normal Ro for no signal is 50,000 ohms. For a plus peak of 15 volts in the plate circuit, Ro equals 77,941 ohms, giving a difference of 77,941 − 50,000 = 27,941 ohms. For the negative peak of 15 volts in the plate circuit, Ro is 35,606 ohms, giving a difference of 50,000 − 35,606 = 14,394 ohms. Thus for a positive peak signal in the plate circuit, Ro is 13,547 ohms (27,941 − 14,394) more away from the normal of 50,000 ohms than it is at the negative peak. This represents a percentage difference of 48.48%.

The foregoing has demonstrated conclusively that the vacuum tube *is not a linear device and is not subject to ohms law.*

Since in one case the maximum peak voltage of the plate signal is 62.5 and the minimum peak is 32.5

volts, it should be clear that for the maximum peak in the positive direction of the cycle, the voltage *lost* across R_L will be $62.5 - 15 = 47.5$, and for the negative peak of the cycle the voltage *lost* across R_L will be $32.5 - 15 = 17.5$ volts. This is only natural because with less voltage on the plate, less current will flow, and consequently, the voltage drop across R_L has got to be less because $E = I \times R$.

With instaneaneous values selected it has been possible from a D. C| viewpoint to show you how a varying signal voltage might be developed at the plate of a triode tube. Since the load R_L is in series with the plate of the tube, whatever voltage variations appear at the plate must also appear across R_L. Thus, a continuous varying amplified voltage occurs across R_L as long as a signal is fed to the grid.

Now that we have the strengthened signal across R_L, what is to be done with it? The answer depends on how the signal is to be used and its frequency. If it is an R. F. (high frequency) signal as assumed in our discussion, the proper procedure is to feed it to another amplifier stage or to a detector, depending on how much amplification is wanted. In either case, the load R_L will be in the form of a coil as shown in Fig. 15.

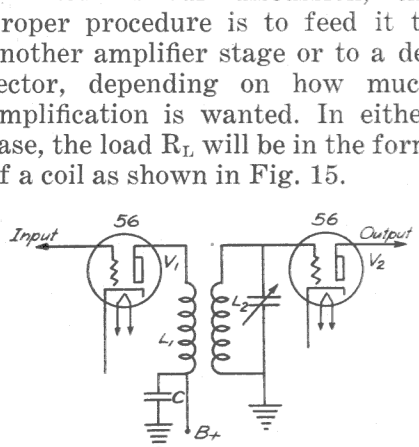


FIG. 15

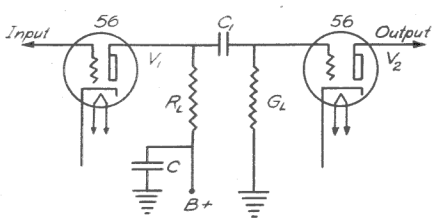


FIG. 16

In this circuit, the changing signal voltage in L1 induces a corresponding voltage in L2 and the circuit of the latter feeds tube V2 which is a duplicate of V1. Two or more stages of amplification are aften required to build a weak signal up to the desired level. In this way, the received signal is gradually built up in strength and eventually reaches the speaker causing it to reproduce sound the details of which you will get in later lessons. The details of the input circuit of tube V1 and the output circuit of tube V2 in Fig. 15 are not shown because the circuit is intended only to show how the signal may be coupled from one tube to another — coils L1 and L2 being the coupling agent in this case.

If the signal had already been fed to a detector it could be coupled to another stage as in Fig. 16. Note in this case R_L — the plate load — is a resistor, and so is the grid G_L in the following stage. In this case, the amplified signal is transferred to tube V2 through condenser C1 electrostatically. Condenser C in Figs. 15 and 16 are for filtering and by-passing purposes as explained for condensers C and C2 in Figs. 3 and 11. Both Figs. 15 and 16 involve several things you have not studied as yet so the details of their operation will be left to later lessons.

GAIN OF A TUBE

The gain of the tube alone is something entirely different from the net or real gain of an amplifier stage which includes not only the tube but also its associated circuit. The amount of increase of the plate voltage over the input grid voltage is naturally the amount of gain of an amplifier stage. This is usually expressed as a voltage ratio or $\frac{Ep.}{Eg.}$ For example, if 5.5 volts is applied to the grid, the corresponding plate voltage may, for instance, be 265 volts. This is an increase of 15 volts over what the plate voltage is when no signal is applied. If the input is 2 volts and the output is 15 volts, the gain in voltage is naturally 15/2 or 7.5 times. This in itself is not a large gain but it does illustrate the amplifying action of a triode tube.

The high D. C. voltage on the plate of a tube is used only to operate the tube. There is no further use for it after the amplified signal has been provided. Thus, in the foregoing example, 15 volts represents the A. C. signal, 250 is lost across the tube as a result of operating it and 32.5 volts is lost across the load R_L. The total supply voltage is, therefore, accounted for because 15 + 250 + 32.5 = 297.5 volts. From this, you will see that out of a total 297.5 volts only 15 volts is useful in transferring the signal to another stage. For the example used, the tube therefore, has an efficiency rating of 5.04% with respect to applied D. C. voltage from the power unit.

Now for one other matter. You may wonder why the grid being at a negative voltage does not stop all electrons from reaching the plate.

Although the grid is being maintained at a negative charge, this negative charge is not high enough to prevent all of the electrons from reaching the plate. The manufacturer of the tube takes care of this by recommending normal operating voltage for the grid. The plate is being maintained at a very high positive charge and overcomes to some extent the effect of the space charge and the negatively charged grid. Therefore, even with no input signal, there is a certain amount of D. C. plate current flowing. *The grid could be maintained at such a high negative charge that no D.C. plate current at all would flow.* This is sometimes done with certain tubes as you will learn later. In an amplifier of the type we have been considering here, a certain amount of D. C. plate current must flow so as to permit the signal to be amplified but at all times it must be under control of the grid.

With a *constant charge* on the grid there will be a certain value of voltage on the plate, the D. C. plate current will be at a fixed value and the Ro of the tube will also be at a fixed value. If the grid charge is changed to some other value, the plate voltage, plate current and the Ro of the tube will change accordingly. Here again the important principle for you to understand at this time is that the *change* of voltage due to a varying A. C. signal on the grid is the agent or tube element which causes Ro to change.

The manufacturer of the tube arranges the elements within the tube so that a very small signal

voltage in the grid circuit will have a tremendous effect on the number of electrons which reach the plate. In other words, a small change in voltage at the grid circuit will create a much larger change in voltage at the plate. The reason it does this, of course, is because the Ro of the tube changes along with the change in the grid voltage. If the Ro changes, then it follows that the plate voltage across R_L must change accordingly because the two resistances are in a series circuit.

This concludes the study of the triode tube from a D. C. viewpoint. Its A. C. characteristics are much more important, because it is the varying A. C. signal in which we are most interested. Therefore, factors which affect the A. C. signal must be given close and careful consideration.

A. C. CHARACTERTICS OF VACUUM TUBES

The three important A. C. characteristics of radio tubes are: (1) *amplification factor* represented by the Greep letter μ (Mu), (2) A. C. *plate resistance* represented by Rp and (3) mutual *conductance* represented by Gm. These three factors are amply demonstrated and defined by the *family of curves* shown in Fig. 17. This information is put out by the Sylvania Electric Products Company, maker of the Sylvania line of radio tubes. The curves shown are for a 7A4 tube which is of the triode type. The term *family of curves* is applied to a graph which includes several curves all relating to the same general theme.

The left vertical scale of Fig. 17 is graduated in units of plate current from zero to 16 milliamperes which is the operating range for the tube. The scale at the bottom of the graph is graduated in units of plate voltage from zero to 350 volts. The seven curves of the graph represent typical negative grid voltage values for the tube. From these curves the exact operating conditions for the tube can be determined. To show how the graph is used consider the −8

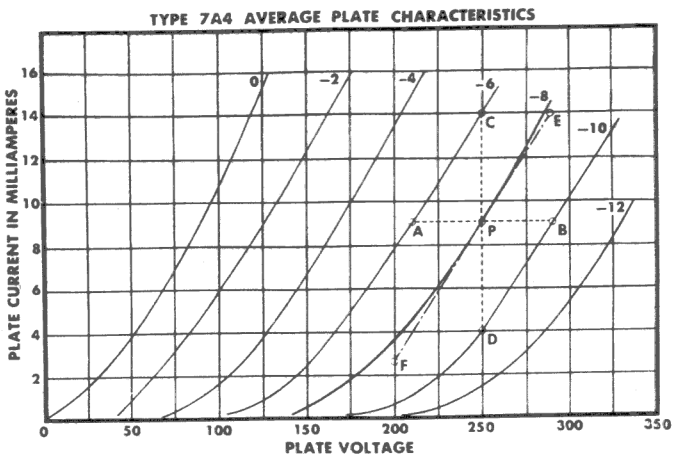


FIG.17

curve. Locate the vertical 250 volt line as read along the plate voltage scale. Follow this line up to the point where it intersects the −8 curve (point P). Then read over from this point on the curve along an *imaginary line* to the vertical current scale and note that the plate current is approximately 9 milliamperes. If the grid is maintained at −8 volts, and the plate voltage is reduced to some value less than 250 volts, the plate current is going to reduce accordingly. It is desirable to know in advance what the corresponding plate current would be when the plate voltage is varied below 250 volts. Suppose the plate voltage is reduced to 225 volts. To find the corresponding plate current with −8 volts on the grid, trace up the 225 volt line in Fig. 7 until it intersects the −8 volt curve and then trace directly over to the left and note the plate current is 6 milliamperes.

In like manner, suppose 275 volts is applied to the plate. Trace up along the 275 volt line to where it intersects the −8 curve and, note the plate current is approximately 12 milliamperes. In a similar manner, the respective plate voltages, plate currents and grid voltages can be determined from the curves for such points as those labeled A, B, C and D on the graph. The Sylvania Electric Products Company gives the following additional information about Fig. 17.

"Points A, B, C, D and P of Fig. 17 will be utilized to show how certain tube charactertistics are obtained. These are μ (mu) Gm, and R_p which predict how a given tube type will perform specific functions. These factors are related to each other by the equation $\mu = Gm \times R_P$. Where Gm is expressed in mhos and R_P in ohms. Thus, if any two of these are known or measured, the third can always be computed. In the following considerations, rather large changes in voltages and currents are used for convenience of explanation. Greater accuracy results when very small changes are employed.

AMPLIFICATION FACTOR

Amplification Factor (μ or Mu) is the ratio of a small change in plate voltage to the corresponding change in grid voltage necessary to maintain constant plate current. Consider line APB in Fig. 17 which is a constant current line for grid voltages from −6 volts to −10 volts for corresponding plate voltages from 210 volts to 290 volts. The change in plate voltage 290 to 210 or 80 volts divided by the corresponding change in grid voltage −6 volts to −10 volts or 4 volts gives a value of 20. Thus:

$$Mu = \frac{80}{4} = 20$$

MUTUAL CONDUCTANCE

Mutual Conductance (Gm) is the change of plate current divided by the required change in grid voltage for a constant plate voltage. Consider line CPD in Fig. 17 which is a constant plate voltage line over which the plate current changes 10 milliamperes (from 14 milliamperes to 4 milliamperes) as the grid voltage is changed 4 volts, from −6 volts (C) to −10 volts (D). Then:

$$Gm = \frac{10 \text{ milliamperes}}{4 \text{ volts}}$$

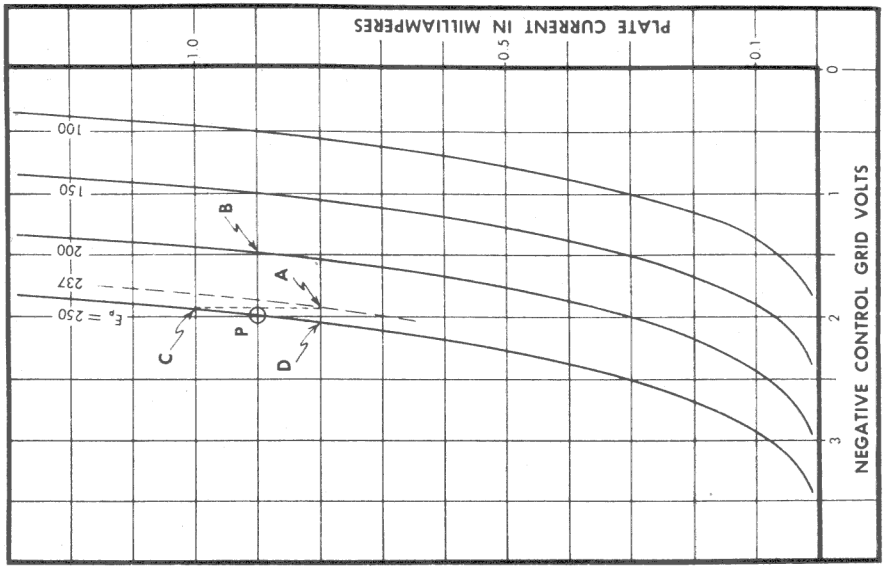


FIG. 18

NOTE: Please refer to Figs. 18, 19 and 20 from the side.

=2.5 milliamperes per volt
=2500 micromhos.

Note:
1 milliampere per volt
= 1000 micromhos
1 microampere per volt
=1 micromho
1 ampere per volt
= 1 mho

A. C. PLATE RESISTANCE

A. C. plate resistance (Rp) may be defined as the ratio of a small change in plate voltage to the corresponding change in plate current produced. It depends upon the grid voltage and plate voltage at the operating point under consideration. Consider the line EPF drawn through point P and just touching the curve at that one point in Fig. 17. The change of plate voltage from E to F is 290 volts minus 200 volts equals 90 volts. The change of plate current from E to F is 14 milliamperes minus 2.5 milliamperes equals 11.5 milliamperes or 0.0115 ampere. Then by Ohms Law:

$$Rp = \frac{90 \text{ volts}}{.0115 \text{ ampere}} = 7800 \text{ ohms}$$

The *mutual characteristic* of Fig. 18 shows plate current versus control grid volts, and each curve is for some specified constant plate voltage. An analysis, quite similar to that given for Fig. 17, provides the following information. Referring to the definitions of μ, G_M and R_P previously given and considering point P on Fig. 18 we compute:

$$\mu = \frac{(250 - 200) \text{ volts}}{PB \quad \text{volts}} = \frac{50}{0.5}$$

$$= 100 \text{ — theoretical gain.}$$

$$Gm = \frac{CA}{DA} = \frac{0.2 \text{ ma.}}{0.133 \text{ volt}}$$

$$= 1.5 \text{ ma. per volt}$$
$$= 1500 \text{ micromhos}$$

$$Rp = \frac{(250 - 237) \text{ volts}}{0.2 \text{ ma.}}$$

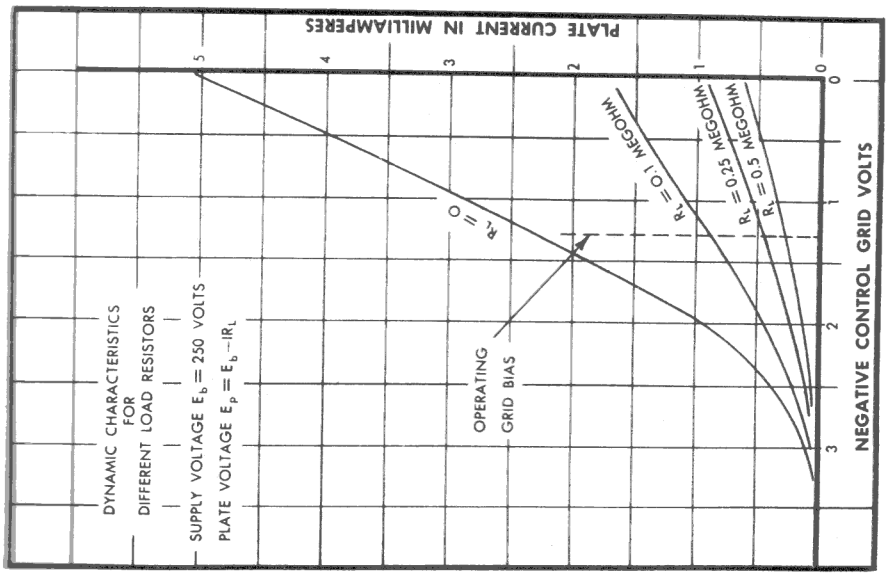


PLATE CURRENT IN MILLIAMPERES
NEGATIVE CONTROL GRID VOLTS
DYNAMIC CHARACTERISTICS FOR DIFFERENT LOAD RESISTORS
SUPPLY VOLTAGE E_b = 250 VOLTS
PLATE VOLTAGE $E_p = E_b - IR_L$
OPERATING GRID BIAS
R_L = 0
R_L = 0.1 MEGOHM
R_L = 0.25 MEGOHM
R_L = 0.5 MEGOHM

FIG. — 19

FIG. 18

$$= \frac{0.0002 \text{ ampere}}{13 \text{ volts}} = 65000 \text{ ohms.}$$

The curves shown in Fig. 19 are known as Dynamic Curves. The static characteristic curves such as those shown in Figs. 17 and 18 are obtained when there is no resistance or impedance in series with the D. C. plate supply. If a resistance load is inserted in the plate circuit the dynamic characteristic no longer resembles the static characteristic curve but is affected by the load, resulting in a more nearly straight curve for the dynamic characteristic. The straighter the characteristic, the smaller will be the amount of distortion present.

The set of curves in Fig. 20 indicates how μ, Gm and Rp vary as a function of the negative control grid voltage. The amplification factor remains fairly constant over a considerable range whereas the mutual conductance decreases rapidly as the grid is made more and more negative. Since μ = Gm × Rp, and μ does not change materially (due to construction of the grid) the Rp must increase as the grid bias is increased."

The mathematical relation between μ, Rp and Gm may be stated as follows:

$$\text{Mu} = \frac{\text{the change in plate voltage}}{\text{the change in grid voltage}}$$

$$\text{Rp} = \frac{\text{the change in plate voltage}}{\text{the change in plate current}}$$

$$\text{Gm} = \frac{\text{the change in grid voltage}}{\text{the change in plate current}}$$

The relation between all three units is similar to ohms law. Thus:

$$\mu = \frac{G_M}{R_P}$$

$$R_P = \frac{\mu}{G_M}$$

$$G_M = \frac{\mu}{R_P}$$

In the study of vacuum tubes it

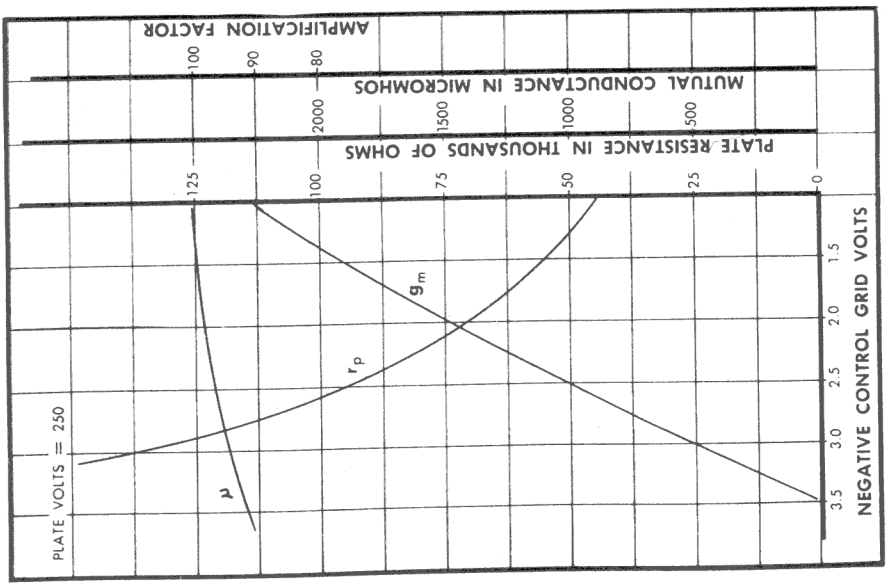


FIG. 20

is necessary to be continually dealing with μ, Rp and Gm. Therefore, you should become thoroughly familiar with just what each means.

The term *mutual conductance* suggests a relation between the two units because of the word mutual. Mutual may be defined as a word which indicates that something is common or related between two or more units. For instance, it may be said that both copper and nickel wire have a certain amount of resistance. Resistance, then, is a mutual property of both types of wire—or it might be said that resistance is a mutual property of all types of conductors.

Conductance, you will remember, is the opposite or reciprocal of resistance. Thus for every resistance value, there is also a conductance value. Instead of thinking of a circuit as offering so much opposition (resistance) to the flow of current, it is just as easy and as convenient to think of a circuit of 500 ohms as having a conductance of 2000 micromhos ($\frac{1}{500}$). Likewise, if a circuit has a resistance of 4000 ohms, it will have a conductance of 250 micromhos ($\frac{1}{4000}$). Either statement is correct as long as the answer includes the proper units—ohms or mhos.

To change from resistance (R) in ohms to conductance (G) in micromhos, use the following formula:

$$G = \frac{1}{R} \times 1{,}000{,}000$$

Study carefully the relation between these two units and you will see that both indicate the rate at which current will flow through the circuit. If a circuit has a high resistance, a relatively small current will flow. If the same circuit has high conductance, a relatively large current will flow if we assume in both cases that the voltage

has remained the same.

Since conductance is the reciprocal of resistance ($\frac{1}{R}$) you might ordinarily think that the mutual conductance of a vacuum tube is equal to $\frac{1}{Rp}$ or the opposite of A.C. plate resistance. This would be true if it were not for the amplification factor of the tube. That is, $\frac{1}{Rp}$ will give us the A. C. *plate conductance,* but it does not take into consideration that the signal is amplified. You must, therefore, take the grid into consideration, and that is where the word *mutual* comes in. A term which includes the effect of the grid (with reference to the A. C. signal) gives the true conductance or mutual conductance of the tube. Another way that this may be stated is that $\frac{1}{Rp}$ gives us the A. C. conductance of the tube, while $\frac{Mu}{Rp}$ gives the mutual conductance of the tube.

Since it is common practice to refer to resistance instead of conductance, you may wonder why the term *mutual resistance* is not used instead of mutual conductance. The reason it is common practice to use Gm is because a tube with a high Gm is a better amplifier tube than one with a low Gm. If the term mutual resistance were used, the tube with the lowest mutual resistance would be the better tube. Further on in the service and repair part of your S. A. R. course you will learn how the Gm value indicates the usefulness of a tube for a given circuit.

Refer again to the diode circuit of Fig. 4. Suppose there is an applied changing A. C. input signal, having a peak value of 20 volts. To illustrate further about the Gm, assume that this A. C. signal causes a plate current change equal to .5 ma. It is clear that if current flows in the space between plate and cathode, this space will have a certain conductivity value. The conductance value in this case is equal to $\frac{20}{.0005}$ = 40,000 ohms and this represents a conductance of $\frac{1}{40{,}000} \times 1{,}000{,}000$ or 25 micromhos.

If a grid is now introduced between the plate and cathode, a triode is formed similar to Fig. 3. The signal in this case is applied to the grid of the tube and again there is a change in the plate circuit voltage equal to 20 volts. In this case, the current is caused to change by an amount equal to 4 milliamperes. Note there is now a much higher conductivity than in the diode circuit. In fact, the resistance is equal to $\frac{20}{.004}$ = 5000 ohms. The conductivity is $\frac{1}{5000} \times 1{,}000{,}000 = 200$ micromhos. In the case of the diode, the conductance was 25 micromhos and in the case of the triode it is 200, or 8 times greater.

The grid is responsible for this increase in conductance. The conductance of the diode was im-

proved by the effect of the grid. The two conductances—that due to the plate circuit and that due to the action of the grid are mutually related — hence *mutual conductance combines these two effects into one term.*

In Fig. 4, 20 volts were applied to the plate, but in Fig 3, it was stated that 20 volts *appeared at the plate.* This was brought about as explained before by the grid voltage being multiplied a certain number of times when it was transferred to the plate circuit. In this case, 5 volts have been applied to the grid to obtain 20 volts at the plate. This gives a signal multiplying power of $\frac{20}{5}$ or 4 times.

For the diode, it was necessary to apply the full 20 volts to the plate circuit as this type of circuit or tube has no multiplying power of its own.

This actual measurable gain or increase in signal voltage when amplified by a tube is its amplifying power or, as it is more commonly called, the *gain of the tube or stage. All of the capability of amplification does not rest with the tube,* but rather with its association to other components to which it is connected.

FACTORS WHICH CONTROL AMPLIFICATION

What things influence the ability of a tube to amplify? You have seen that the tube itself has an inherent property or characteristic which permits it to amplify. This is determined by the position and structure of its elements, grid, plate, spacing, size, etc. This capability of the grid to bring about a larger voltage in the plate circuit is called the *amplification factor of the tube.* The amplification factor of a tube can never be attained, but it can be closely approached. The reason for this is that the actual amount of voltage gain or amplification is determined partly by the tube itself and partly by the ratio of the external plate load resistance, R_L, to the entire plate circuit. The ratio is $\frac{R_L}{R_L + Rp}$ where $R_L + Rp$ make up the entire plate circuit. It is simply the sum of the internal A.C. plate resistance and the external load resistance as they are connected in series.

This principle of ratio of resistance is very important because by making a study of it you will understand the function of a triode tube much better. The principle involved is what relative values must two resistors have for a maximum change in voltage to take place for a given change in value for one of the resistors? The ratio of the load voltage to the entire voltage is

$$\frac{E_L}{E_L + Ep}$$

Since a uniform current is flowing through both resistors the resistance values have the same ratio, namely,

$$\frac{R_L}{R_L + Rp}$$

Fig. 14 is a simplified circuit used to illustrate this principle in which Rp is used to replace R_o. When the value of the resistance ratio is *maximum* you know from the foregoing voltage equation that the voltage change due to a given resistance is maximum. Several values for the R_L of a triode tube

R_L	Rp	$\frac{R_L}{R_L + Rp}$			Ans.
2,000	10,000	$\frac{2,000}{2,000 + 10,000}$	=	$\frac{2,000}{12,000}$	=.1666
5,000	10,000	$\frac{5,000}{5,000 + 10,000}$	=	$\frac{5,000}{15,000}$	=.333
10,000	10,000	$\frac{10,000}{10,000 + 10,000}$	=	$\frac{10,000}{20,000}$	=.5
50,000	10,000	$\frac{50,000}{50,000 + 10,000}$	=	$\frac{50,000}{60,000}$	=.9375
1,000,000	10,000	$\frac{1,000,000}{1,000,000 + 10,000}$	=	$\frac{1,000,000}{1,010,000}$	=.99

are given in the above table. Note how the ratio of the resistance changes for different values of R_L.

These examples prove that the resistance ratio can never exceed 1, because the denominator of the fraction also has the value of the numerator included with it. However, it may approach 1 as R_L is increased.

The amount of *actual gain* of any amplifier stage is, therefore, equal to:

$$\text{Gain} = \text{Mu}\frac{R_L}{R_L + Rp}$$

where Mu is the symbol for the theoretical amplifying power of the tube. With this information, the actual amplifying power of a circuit using *any tube* may be plotted in graph form for any load or R_L value. The resulting curve is shown in Fig. 21. By making use of this curve, the gain of an amplifying circuit can be predetermined before the circuit is built. The curve is used in the following manner. If, for instance, R_L should be 10,000 ohms, with Rp also equal to 10,000 ohms, the ratio

$$\frac{R_L}{R_L + Rp}$$

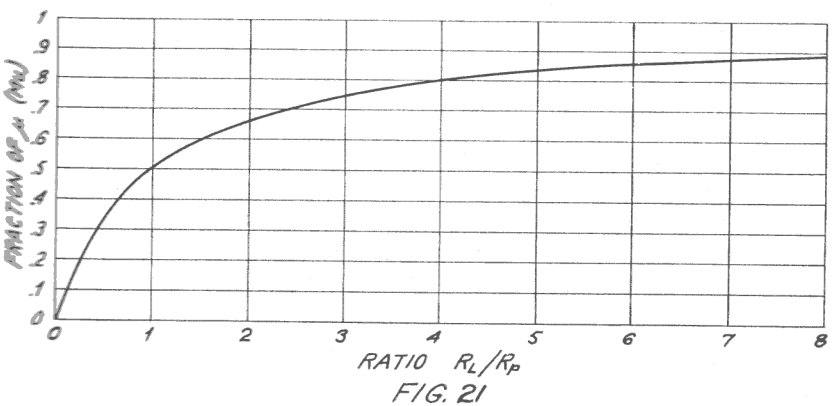


FIG. 21

would equal

$$\frac{10{,}000}{10{,}000 + 10{,}000} = \frac{10{,}000}{20{,}000} = 0.5.$$

Throughout this lesson we have referred to Ro as the D. C. plate resistance and to Rp as the A. C. plate resistance. It is most important that you understand that these are entirely separate resistance values. The Ro (internal D. C. plate resistance) limits the flow of D. C. plate current from the plate battery. Ro also changes in value with variations of input signal. Rp or the A. C. plate resistance limits the flow of effective A. C. or pulsating D. C. *This value remains practically the same within operating limits of the tube.* The Gm of a tube does change during the life of a tube, and as it decreases in value, the tube begins to lose its effectiveness. When it drops to a minimum for a given type of tube, it will need replacing with a new tube as will be explained in your service course lessons.

Now that you understand more about amplification you are ready to learn more about other characteristics of a tube. Fig. 22 illustrates the next step in your study. This graph shows the Eg-Ip curve of a tube, meaning *the grid voltage versus the plate current characteristic of a tube.* Be sure to remember this definition of an Eg-Ip curve.

Note the curve at about the center of the figure. It shows the manner in which the plate current (Ip) varies with grid voltage (Eg). Each type of amplifying tube has one of these curves (published by

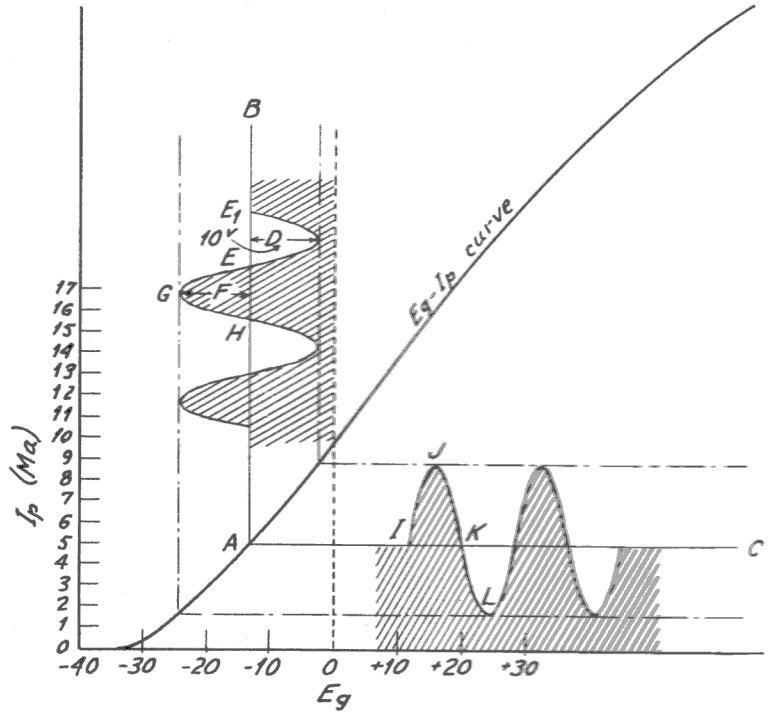


FIG. 22

tube manufacturers) and they will be of different shape for different type tubes. By studying a curve of this type you can tell from it just what the tube will do under a given set of conditions. The manufacturer of the tube plots these curves and they are standard for the type of tube which they represent.

The way these curves are plotted is as follows: The tube is connected into a circuit with a certain plate voltage applied. The negative grid voltage is then varied over a wide range as indicated along the horizontal line of Fig. 22. The plate current is then plotted with reference to the vertical axis. After a number of points have been plotted, a curve such as that shown in Fig. 22 is obtained.

To show the complete action of the tube, an A. C. grid voltage E_1 and the resulting plate current variation I are also plotted in Fig 22. The A. C. signal voltage is plotted along the vertical line A-B, corresponding to the 13.5 volt negative grid voltage used in previous examples. The pulsating plate current of the tube is plotted along the horizontal line A-C. This corresponds to the no signal plate current flowing with 13.5 volts negative bias on the grid or 5 ma.

Now with this in mind, suppose an A. C. signal voltage of 10 volts peak is applied to the grid of the tube as shown at D on the input A. C. wave form. On the positive half of the cycle represented by the distance D, the effective bias on the grid of the tube changes from 13.5 volts negative to 3.5 volts negative (this point on the grid voltage scale of the graph needs to be estimated). The A. C. grid voltage then begins to decrease, which means that the total negative grid voltage is now increasing from 3.5 volts negative towards 13.5 volts negative because the A. C. input of 10 volts positive is gradually reducing. The actual grid voltage wave form resulting is shown by the shaded wave along the line A-B. When the A. C. grid voltage has reduced to the point E, it is zero, and the effective grid voltage is the normal 13.5 volts negative which is supplied by the battery.

Next consider the negative half of the A. C. cycle. This is represented by the distance F on the grid voltage wave form. At the point G the total voltage on the grid of the tube has increased to 23.5 volts negative (negative peak of the A. C. signal plus the normal bias). When the A. C. signal voltage reaches point H on the wave form, the voltage on the grid is again at the applied value of 13.5 volts negative. This description of the action of the grid shows what happens for one cycle. Succeeding cycles act on the grid in a like manner.

Again you will note that an A. C. signal voltage increases and decreases the total effective grid voltage of a tube. Remember, too, that this increase and decrease is in relation to the battery or C voltage applied to the grid. In other words, the A. C. signal voltage adds to and subtracts from the battery voltage applied to the grid. In the example of Fig. 22, an A. C. signal voltage of 10 volts is applied to the grid to get a *total effective change of 20 volts in the grid circuit* (13.5 $-$ 10 = 3.5 and 13.5 + 10 $-$ 23.5.

Thus $23.5 - 3.5 = 20$ volts total change).

Next consider what has happened to the plate current while the grid voltage has been changing. It has been mentioned that as the *grid become less negative, the plate current increases,* and if it becomes *more negative, the plate current decreases.*

The plate current wave form (I) of Fig 22 shows how the plate current follows the exact variations of the A. C. grid voltage. As the A. C. signal voltage changes from D to F on the grid voltage wave form, the plate current wave form increases to J and then reduces to L. Notice that the entire grid voltage range is *projected* down on the Eg-Ip curve of the graph and then the points of intersection are projected to the right, representing the entire plate current range. Any point of the grid voltage wave form projected in this way will show the corresponding plate current value determined by the Ep-Ip characteristic. Thus every part of a complete grid voltage wave may be projected on the curve to determine the exact plate current variation over the range of the grid voltage. Be sure to keep this basic wave form of the Eg-Ip curve in mind because you will find continual reference to it in your radio work from time to time.

These questions are designed to test your knowledge of this lesson. Read them over first to see if you can answer them. If you feel confident that you can, then write out your answers, numbering them to correspond to the questions. If you are not confident that you can answer the questions, re-study the lesson one or more times before writing out your answers. Be sure to answer every question, for if you fail to answer a question, it will reduce your grade on this lesson. When all questions have been answered, mail them to us for grading.

QUESTIONS

No. 1. Name the two factors which primarily determine the gain of an amplifying stage.

No. 2. Define the D. C. plate resistance Ro and the Rp or A. C. plate resistance of a diode or triode tube.

No. 3. In what two ways does the amplified signal voltage differ from the input grid signal voltage of an amplifier?

No. 4. For the greatest voltage amplification, should the plate load resistance RL be made high or low?

No. 5. What signal voltage may be expected at the plate of a triode tube if a ½ volt signal is fed into the input—the tube has an Rp of 12,500 ohms, an RL of 50,000 ohms and a Mu of 40? (Hint—use Fig. 21.)

No. 6. For an equal variation in grid and plate voltage, which variation will cause the greater change in plate current?

No. 7. Refer to Fig. 22 and determine what value of plate current would flow if the grid were made 35 to 40 volts negative.

No. 8. Briefly explain what is meant by the mutual conductance (Gm) of a tube.

No. 9. State where the grid is located in a tube with reference to the position of the plate and cathode.

No. 10. Why may electrons pass through the grid structure even though it is always maintained negative?